# The Concept of Tokamaks with the Lithium Walls

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#### **Abstract**

At present, there is a significant frustration about reactor prospectives of the tokamaks which were studied extensively since late of 60s. Leaving aside nuclear engineering aspects of the tokamak reactors, it is possible to conclude that none of the most fundamental plasma physics issues, such as energy extraction from the plasma, plasma refueling, helium exhaust, controlling the stability and the electric current, has yet been resolved for the tokamak-reactors even at the conceptual level.

Over past two decades, the concept of the tokamak-reactor became entirely associated with the divertor configurations. In fact, the divertor is in conflict with many basic requirements. Thus, instead of distributing the power deposition on the inner wall, the divertor concentrates it. Instead of increasing the edge temperature of the plasma in order to suppress the anomalous transport, the divertor requires just the opposite. For the helium exhaust, the divertor concept allows the thermalization of the alpha-particles, what makes them indistinguishable from D and T ions of the plasma. Then, the divertor concept relies on some magic properties of the highly non-equilibrium scrape of layer, which would resolve the problem of the power and helium extraction from the plasma.

The existing approaches also failed to solve the problem of the central refueling for the reactor control and again relies on some inefficient high tech means for affecting the fusion rate and the plasma profiles.

From the pragmatic point of view, now dominant, biased toward the divertor, concept of the tokamak-reactors played a grave role in shutting down TFTR, the major US fusion experiment, as well as in destruction of all the US tokamaks with the circular cross-section (TEXT, PLT and, now, TFTR).



#### **Abstract**

Being alternative to the divertor, the concept of the tokamaks with the lithium walls (LiW), which is intrinsically originated from the results of TFTR experiments with the Li pellets, has been triggered by new ideas from the APEX program. In Dec. 1998, it was understood, that the lithium represents the unique metal, which can be propelled at the necessary speed along the plasma facing walls and, thus, can potentially solve the problem of the energy extraction. In agreement with the TFTR results, the lithium (solid or liquid) can dramatically affect the plasma confinement and stability regime by low recycling wall conditions and by enabling conducting stabilizing wall at the plasma boundary. For the first time, with the LiW, the expected plasma density and temperature profiles could be in consistency with suppression of anomalous energy transport and with enhanced stability, both required for the commercially efficient fusion reactors.

The concept of LiW tokamaks initiates in a new way the solution of the problem of the central refueling for the reactor control. It reveals the remarkable properties of the magnetized Morozov's rings, which can serve as the transporters of the fuel as well as the potential means for the helium exhaust (see two separate abstracts for ICC2000 on Morozov's ring).

The the key points of the LiW tokamak concept will be presented to ICC2000.



#### **OUTLINE**

- 1. Preface.
  - (a) Why Li?
  - (b) Why Li walls?
- 2. The concept of tokamaks with Li walls.
  - (a) Plasma profiles in the non-recycling regime.
  - (b) Central refueling.
  - (c) High- $\beta$  (15-20 %) tokamak operation.
  - (d) Intense lithium streams in tokamaks.
  - (e) Lithium covered walls in tokamaks.
  - (f) Tokamak-reactors with the Li walls.
- 3. TFTR lithium pellet experiments.
- 4. Summary.



### 1. Preface

While the tokamak represents the most developed plasma fusion concept, its reactor applications

still do not address in a clear way
the solution of the problem of extraction
of the thermal energy

from the high temperature plasma

at the reactor relevant levels

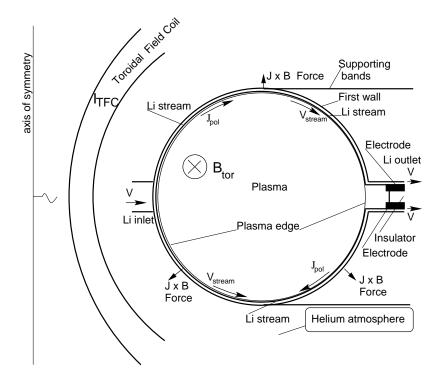
of the energy fluxes of several MW/m<sup>2</sup>.



The effect of magnetic propulsion suggests

#### a new way of resolving this problem

by using intense lithium streams along the plasma facing surface of the vacuum chamber of tokamaks.





#### The physical properties of the liquid lithium

low melting temperature	$T_{melt}$	$\simeq 180^{o} C$
low density	ρ	$\simeq 0.53 \ g/cm^3$
low viscosity	ν	$\simeq 0.0004 \ Pa \cdot sec$
high thermal capacity	$c_p$	$\simeq 4200 J/(kg \cdot K)$
high thermal conductivity	$\kappa$	$\simeq 47 \ W/(m \cdot K)$

#### make lithium potentially

#### the best coolant

for tokamaks, while

optimal electroconductivity 
$$\sigma \simeq 3.3 \cdot 10^6 \ (\Omega \cdot m)^{-1}$$

#### makes it

#### the only liquid metal

which can be propulsed at necessary speed of 20 m/sec in the strong magnetic field of tokamaks.



The required high velocity, 20 m/sec, is determined by necessity of keeping the temperature of the plasma facing surface of the streams

below limits of essential evaporation of the lithium

$$\Delta T_{Li} = 2q_{wall} \sqrt{\frac{t_{transit}}{\pi \kappa \rho c_p}} < 150 - 200^o, \tag{1.1}$$

#### where

 $q_{wall}\,\,$  - the thermal power flux on the wall

 $t_{transit} = \int_{inlet}^{outlet} rac{ds}{V(s)}$  - the transit time of the fluid element.

$$q_{wall} = 3.5 \ MW/m^2$$

$$\begin{array}{rl} a &= 1.6 \ m \\ V &= 20 \ m/sec \\ t_{transit} &= 0.25 \ sec \end{array}$$

$$\Delta T_{Li} = 200^{\circ}$$

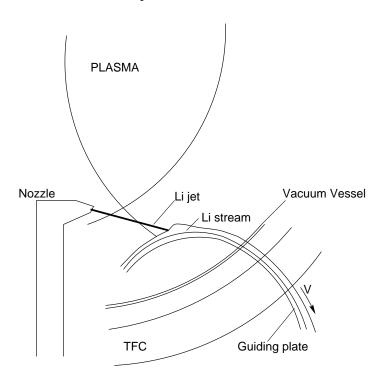


#### Reason 1. Distributed power deposition.

Concentration of power deposition is highly unfavorable

$$q_{wall} \to C q_{wall}, \quad t_{transit} \to t_{transit}/C^2, \quad V \to CV$$

Lithium jets in divertor will not work in a reactor



Lithium walls have a chance to work in fusion reactor.



#### Reason 2: Absorption of the plasma particles

Lithium is unique in absorbing all H, D, T particles and converting them into solids LiH, LiD, LiT.

Velocity of 10-20 m/sec is sufficient for refreshing the surface of the lithium, so only several monolayers of the lithium should be converted into LiD or LiT in order to absorb the entire flux of the hydrogen particles from the fusion plasma.

Stationary non-recycling regime seems to be posible with intense Li streams at the walls

University of Illinois Urbana-Champaigne studies sputtering on Li which appears to be small.



Reason 3: MHD stabilization of the plasma boundary by the conducting wall right at the plasma edge

For high frequencies

$$\omega > \frac{1}{\tau_{wall}}, \quad \tau_{wall} \equiv \frac{\mu_0 \sigma h a}{m} \simeq \frac{4ha}{m}$$
 (1.2)

Li is almost perfectly conducting

$$\tilde{\mathbf{B}} = \nabla \times (\vec{\xi} \times \mathbf{B}). \tag{1.3}$$

At the highly preloaded guide plate, the normal displacement of Li

$$\xi_{+}^{n} = 0, \quad \xi_{-}^{n} = 0, \tag{1.4}$$

and thus the normal component of the magnetic field

$$\tilde{B}^n = (\mathbf{B} \cdot \nabla)\xi^n = 0. \tag{1.5}$$

The plate (conducting or not conducting) becomes equivalent to a perfectly conducting wall at the plasma boundary.



#### Resistive wall modes.

For frequencies lower than the transit time of the flow,

$$\omega < \frac{Vm}{a},\tag{1.6}$$

the flow makes essential stabilizing contribution if

$$Re_m = \mu_0 \sigma h V > 1. \tag{1.7}$$

Condition of overlapping low and high frequencies is

$$Re_m = \mu_0 \sigma h V \simeq 4hV > 1. \tag{1.8}$$

The velocity of 10-20 m/sec for  $h>1\ cm$  is consistent with the condition of overlapping.



#### Reason 4: New approaches for He exhaust

The existing approach for He exhaust: first, cooling 3.5 MeV  $\alpha$ -particles to the plasma temperature (thus, mixing He with D,T), then, pumping this mixture from the scrape of layer and then, cooling it to cryogenic  $4^o$  K

(10 orders of magnitude in temperature)

Liquid lithium walls allow deposition of energetic particles, like cooled, but not mixed with the bulk plasma,  $\alpha$ -particles.

Liquid walls raise expectations (ALPS, T-11) for solving Helium exhaust problem in a new way.



## 2. The concept of a tokamak with Li walls.

- Intense lithium streams at the plasma boundary
- + Non-recycling regime with suppressed thermo-conduction
- + Central (not boundary) refueling
- + Wall stabilization of free-boundary MHD.

As the first, but significant step, the test of the concept can be done on existing machines with no liquid lithium flow but with

- Lithium covered (e.g., copper) walls and Li pellet injection
- + Non-recycling regime with suppressed thermo-conduction
- + Central (not boundary) refueling
- + Wall stabilization of free-boundary MHD.



With the ideally absorbing walls, i.e., in the non-recycling regime, the plasma profiles are determined by the particle continuity equation

$$\Gamma \equiv Snv = const = (\Gamma)_a, \tag{2.1}$$

where the central fueling of the plasma is assumed, and by the energy balance

$$\frac{5}{2}\Gamma T - S(\kappa_T \nabla T + \kappa_n \nabla n) = \int_0^r P dv$$
 (2.2)

At the edge there is no thermoconduction terms

$$\left(\frac{5}{2}\Gamma T\right)_a = \int_0^a P dv \tag{2.3}$$

and

the energy confinement time in this regime is determined by the particle confinement.

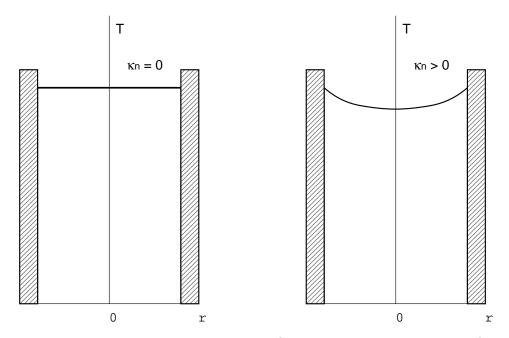
**Energy transport equation** 

$$\frac{5}{2}\Gamma T - S(\kappa_T \nabla T + \kappa_n \nabla n) + \int_r^a P dv = \left(\frac{5}{2}\Gamma T\right)_a. \tag{2.4}$$



In a model case with  $\delta$ -functional energy and particle sources, the temperature profiles has inverse gradient, which compensates the thermal conduction

$$\frac{5}{2}\Gamma(T - T_a) - S(\kappa_T \nabla T + \kappa_n \nabla n) = 0.$$
 (2.5)

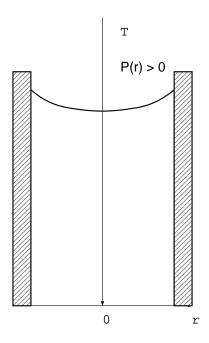


For  $\kappa_n = 0$ , the solution is the flat temperature profile, while for  $\kappa_n > 0$ , the temperature gradient is inverse.



A diffuse energy source in the non-recycling regime also leads to inverse temperature profiles

$$\frac{5}{2}\Gamma T - S(\kappa_T \nabla T + \kappa_n \nabla n) + \int_r^a P dv = \left(\frac{5}{2}\Gamma T\right)_a. \tag{2.6}$$





Thus, in the non-recycling regime, the density profile (assuming central fueling) is determined by

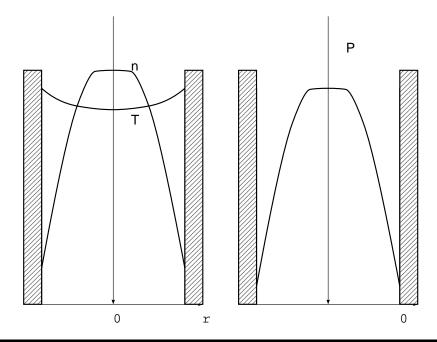
$$n = \frac{\Gamma}{Sv_{diff}},\tag{2.7}$$

the temperature profile has inverse gradient

$$T' < 0, \tag{2.8}$$

and the pressure profile is peaked and has a finite pedestal at the plasma edge

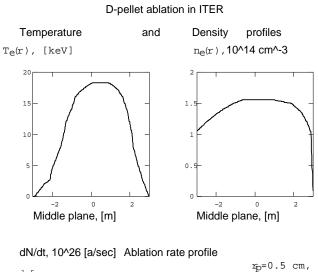
$$p(a) > 0. (2.9)$$



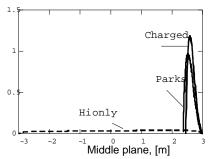


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The problem of plasma refueling as well as of plasma profile and burn control in the fusion reactors does not have even a conceptual solution.



Pellet penetration into ITER plasma

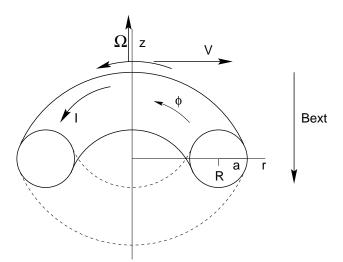


For "hi" ablation only: Initial number of atoms Np0=3.1\*10^22 Final number of atoms Npf=1.1\*10^22



Li wall concept stimulated new idea for refueling and plasma profile control.

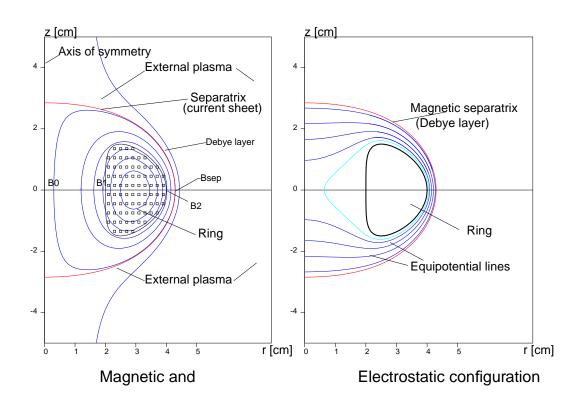
E.g., an idea of A.I.Morozov (1988, published in 1991) of magnetized autonomous probe inside the high temperature plasma seems to be relevant.



Morozov's conducting ring with an electric current and gyroscopic rotation. Magnetically insulated from electrons. Electrostatically insulated from ions.

Can deliver the fuel to any point in the plasma core.





R [cm]	3	$B_{ext}$ [T]	5	$\Psi$ [Vsec]	0.0135
a [cm]	1	$I\left[ MA ight]$	0.605	$\Psi_{ext}$ [Vsec]	-0.0135
b [cm]	1	$B_0$ [T]	7.183	$W_{lpha}$ [J]	80.58
$T\mathrm{[kV]}$	30	$B_1$ [T]	10.47	q [C]	4.605e-05
$ ho_e$ [cm]	0.0067	$B_2$ [T]	-9.69		
$ ho_D$ [cm]	0.406	$B_{sep}$ [T]	-8.707		
$ ho_T$ [cm]	0.497	$U{ m [MV]}$	1.75		
$ ho_{lpha}$ [cm]	2.195	$N_{lpha}$	1.439+14		

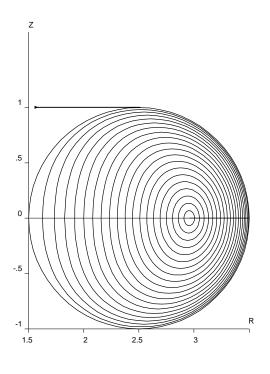


With flat of hollow current distribution

$$j_{||} \propto T^{3/2}$$
 (2.10)

and with a conducting wall at the plasma edge, the plasma exhibits superior stability even in the circular cross-section.

We present an analysis of ballooning and  $n=1,2,3 \ \mathrm{MHD}$  stability for TFTR geometry.



Magnetic surfaces in the poloidal cross-section of TFTR plasma



Codes used for stability calculations of TFTR non-recycling configurations

- Esc equilibrium
- BALLON, DCON ballooning stability
- PEST-II, DCON n=1,2,3 stability

For conventional walls TFTR was getting unstable at

$$\beta > 1 \%. \tag{2.11}$$



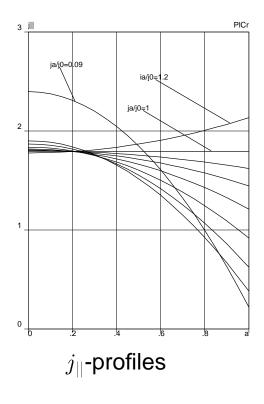
The current density profiles have been chosen as

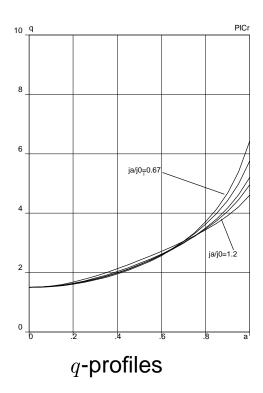
$$j_{\parallel}(a) = j_a + (j_0 - j_a)(1 - a^2)$$
 (2.12)

with ratio  $j_a/j_0$  as a parameter and  $q_0=1.5$ .

$$\frac{dp}{d\Psi} = const, \quad a = \sqrt{\frac{\Phi}{\Phi_{edge}}},$$
(2.13)

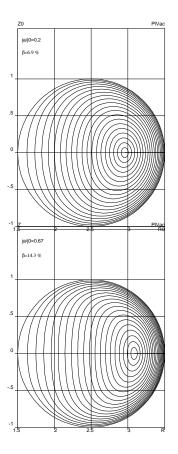
where  $\Phi$  is the toroidal flux.

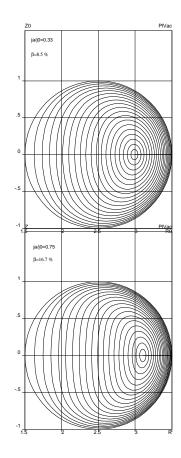


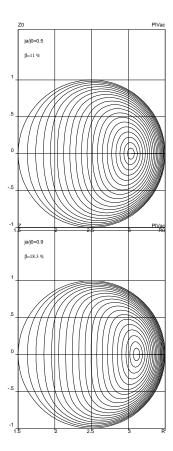




## Marginally stable high $\beta$ configurations with increase in the current density pedestal

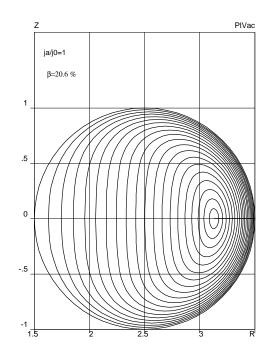


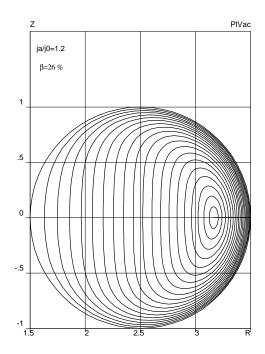






#### Marginally stable high $\beta$ configurations

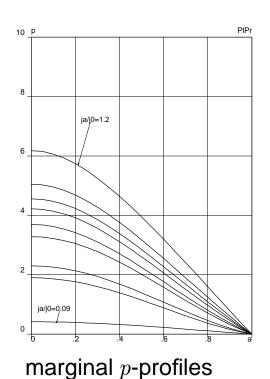


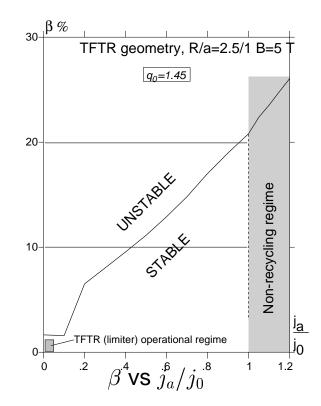


relevant to the non-recycling regime



The stable pressure dramatically increases with increase in the edge temperature pedestal.



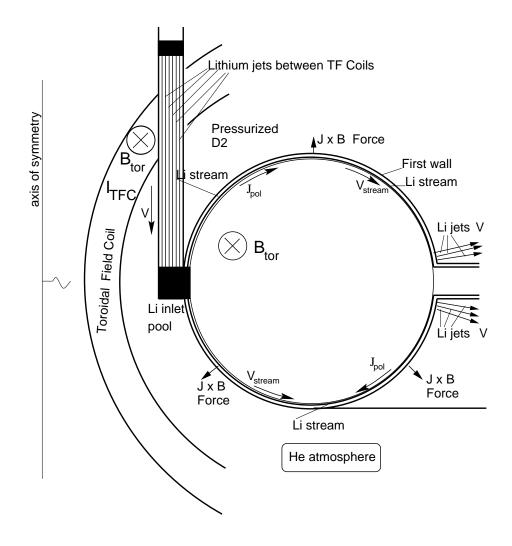


$$\beta \equiv \frac{2\mu_0 \langle p \rangle}{B_{ext}^2},\tag{2.14}$$

where  $\langle p \rangle$  is the volume averaged pressure.



## 3. Intense lithium streams in tokamaks



Pumps are problematic inside the toroidal field of tokamaks.

$$p_w|_{outlet} > 1 \ atm \tag{3.1}$$



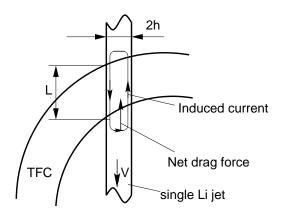
Only fast and thin (h = 2 - 3 mm) lithium jets seems to be a practical way of delivering lithium to the inlet of the vacuum chamber as wells as for ejecting it.

Induced electric current results in loss in kinetic energy

$$\Delta \frac{\rho V_z^2}{2} = -\langle P_r \rangle \frac{B_0^2}{2\mu_0} \tag{3.2}$$

leads to a fundamental condition

$$P_r = \frac{\mu_0 \sigma h^2 V}{L} \ll 1 \tag{3.3}$$

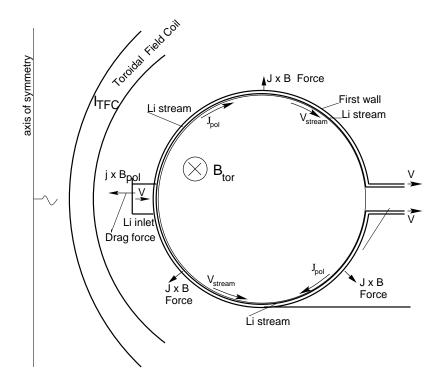




Inside the inlet to the vacuum chamber, the lithium flows across the poloidal magnetic field  $B_{pol}$  of the plasma current. This induces the toroidal current in the lithium

$$j_{\varphi} = \sigma V_{\perp} B_{\perp}. \tag{3.4}$$

Poloidal magnetic field stops even a fast stream at 1-2 cm and redirect it along the magnetic surfaces.





Inside the vacuum chamber the dynamics of the lithium streams is well understood

The velocity for a stationary flow

$$\frac{\rho}{2}V^2 = \frac{\rho}{2}V_{inj}^2 + \frac{\bar{F}_w[\bar{I}_0 - \bar{I}(n)]}{\mu_0} \left(\frac{1}{r_{inj}^2} - \frac{1}{r^2}\right)$$
(3.5)

corresponds to propulsion into lower magnetic field.

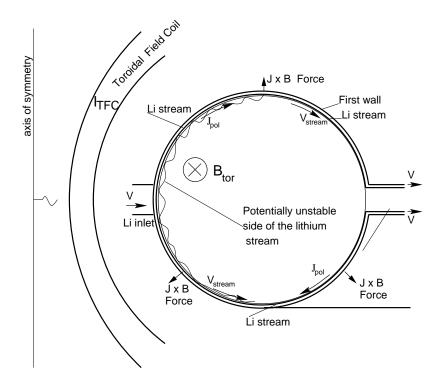
Drag force due to magnetic pumping is negligible if

$$P_D \equiv \frac{\pi}{24} \frac{\mu_0 \sigma h^2 V}{r} \frac{I_{TFC}}{I_{stream}} \ll 1. \tag{3.6}$$



The centrifugal force robustly stabilizes the sausage instability of the stream if

$$\int_{-1}^{\bar{n}} \left( \rho \kappa_w V^2 - 2p \frac{z_w'}{r} \right) d\bar{n} > 0, \quad \kappa_w r \rho \frac{\langle V^2 \rangle}{2} > \frac{p_w}{2} z_w', \quad (3.7)$$





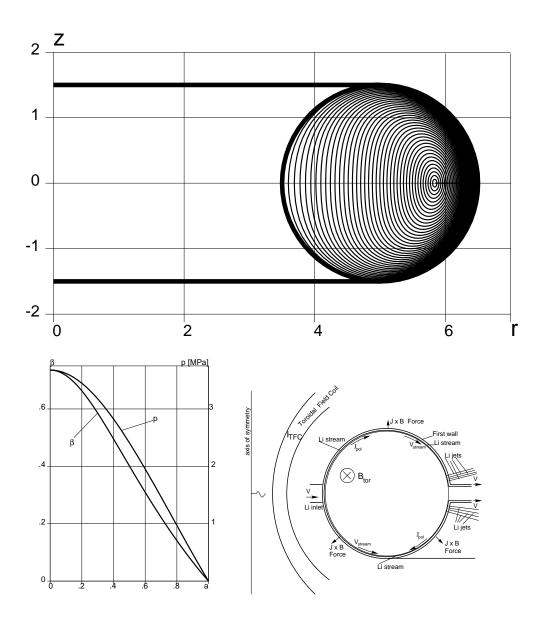
Copper wall at the edge of the plasma with sputtered lithium can

- accept 10 times higher energy flux than the liquid lithium wall
- provide robust stabilization of free boundary modes and in combination with the lithium pellets can simulate the lithium wall non-recycling conditions.

Relatively modest modifications are required for existing tokamaks in order to test a new physics of magnetic confinement

Tokamaks with circular cross-section (such as recently destroyed in the US TEXT, PLT, TFTR) are most suitable for these research







#### Test tokamak-reactor

а	1.5 m		
R	5 m		
В	5 T		
lpl	8 MA		
<n></n>	$2 \cdot 10^{20} \ m^{-3}$		
Т	25 keV		
$\beta$	16 % (limit 22 %)		
$\mid  au_E \mid$	1 sec		
$P_{\alpha}$	0.5 GW		
$P_{neutron}$	2.0 GW		
$oxed{q_{wall}}$	<b>2.5 MW/m</b> 2		
$I_{stream}$	1.5 MA		
$V_E$	14 Volts		
$V_E \cdot I_{stream}$	21 MW		
$V_{Li}$	20 m/sec		
$R_{c-sol}$	2 m		
$B_{c-sol}$	$\pm$ 6 T		
$t_{f-top}$	> 1 hour		



Implementation of the technology of Lithium walls (liquid or solid) can lead to completely new regimes and design of the tokamak-reactors which can be distinguished by

- (a)  $\beta \simeq 15 20 \%$
- (b) high temperature at the plasma edge
- (c) suppressed thermo-conduction transport
- (d) absence of conditions for sawtooth oscillations
- (e) absence of necessity for plasma profile control other than by fuel injection
- (f) absence of the non-inductive current drive
- (g) generation of Volt-second by the bootstrap current
- (h) circular cross-section and by absence of the divertor
- (i) . . . .

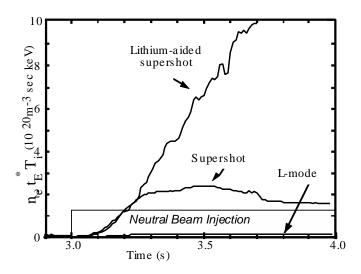
These features would make realistic tokamak-reactors with a low unit power of the order of 300 MW in  $\alpha$ -particles, with much simpler control and commercially competitive with the other power sources.



## 4. TFTR lithium pellet experiments

TFTR was initiator of operations with injection of Li pellets and has shown remarkable improvement in confinement.

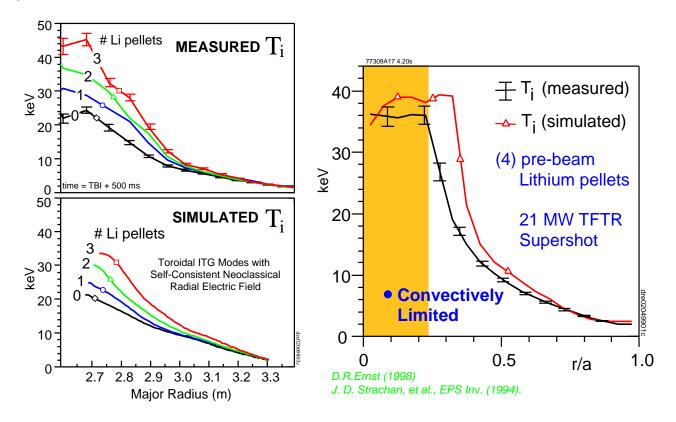
Charles Skinner, Richard Majeski, Robert Kaita, Henry Kugel



- Li conditioning most important factor in TFTR performance.
- Explore plasma lithium surface interactions before complications of introducing large-scale liquid lithium.



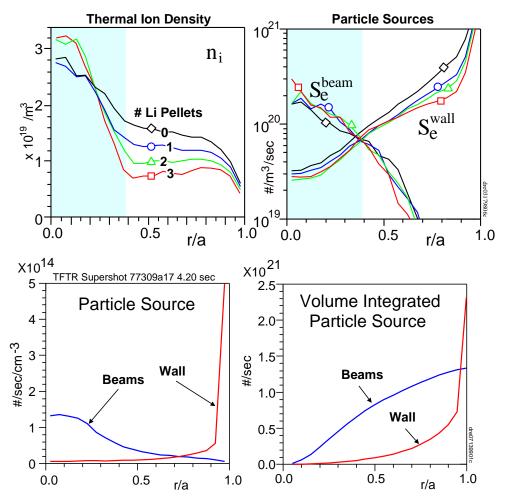
Li pellets at the plasma edge affected the central ion temperature



With 4 pellets the TFTR started to develop a flat themperature profile in the central core.



TFTR did not approach the central fueling conditions and low-recycling



Total Wall Fueling is Twice Total Beam Fuleing (even with 4 pellet)



With Li Wall it was possible to expect on additional jump in TFTR performance.

Achievement of the non-recycling conditions and elimination of the energy thermo-conduction transport can improve the energy confinement time by a factor of 4.

At the same heating power of 40 MW, with no limitation on  $\beta$ , the density can be increased by the same factor of 4.

Thus, the ignition parameter can be increased by the factor of 16, thus, giving expectations for Q=4, which is very close to ignition itself.

The most unfortunate thing is that at present TFTR (the only remaining circular tokamak of the reactor scale) is under destruction and the opportunity to make a breakthrough in magnetic fusion has been misses.



## 5. Summary

Are the lithium walls just a minor modification of existing approaches?

#### No

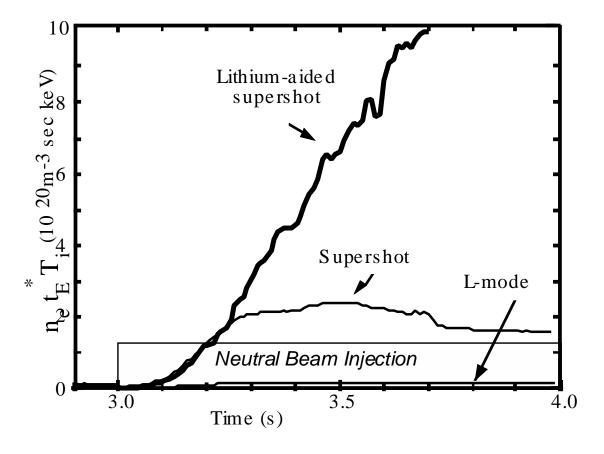
The concept of tokamaks with lithium walls is a response to a reality

- of significant frustration about reactor prospectives of tokamaks
- and rejection of conventional fusion approaches (trapped in low  $\beta$ 's) by society

Instead of participation in ongoing compaign of destruction of the tokamak program in the US, the concept of the tokamaks with lithium walls reveals tremendous potential of new regimes with high temperature and low recycling at the plasma edge.



With all damage already made, the program of tokamaks with lithium walls, continuing the line of TFTR, the major US fusion experiment, should be reinitiated.



Potentially, this will lead to a new strategy and, thus, open new opportunities for the both tokamak and alternative magnetic fusion.

